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TECHNICAL NOTE

No. 1411

THE SPOT WELDING OF ALCLAD 24S-T IN THICKNESSES OF
0.064, 0.081, AND 0.102 INCH

By W. F. Hess, R. A. Wyant, and F. J. Winsor
Rensselaer Polytechnic Institute



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THE SPOT WELDING OF ALCLAD 24S-T IN THICKNESSES OF

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SUMMARY

The present work was undertaken to determine the spot-welding characteristics of heavy gages of Alclad 24S-T aluminum alloy. The weldability of this alloy in thicknesses of 0.064, 0.081, and 0.102 inch was investigated insofar as the capacity of the machine would permit. The welder had a total electrode-force capacity of 5000 pounds and a maximum peak-current output of 74 kiloamperes, using a condenser capacitance of 2640 microfarads, a condenser voltage of 3000, and a transformer-turns ratio of 450:1.

The results of the investigation indicate that high-strength spot welds, free from cracks, expulsion, and excessive sheet separation were obtained in the 0.064-inch material over a wide range in welding current when optimum welding conditions were used in conjunction with electrode tips having a spherical contour $\frac{1}{4}$ inches in radius.

With the same tip contour, high quality welds were obtained over a somewhat narrower current range in welding the 0.081-inch thickness with optimum conditions. In order to secure very strong welds of good quality in this thickness, the use of 6-inch-radius domes was required, but equipment limitations prevented welding under optimum conditions with these tips. The range of shear strengths obtained was considerably higher than with $\frac{1}{4}$ -inch tips, but there was insufficient current capacity to permit the use of an optimum weld force and insufficient forge-force capacity to eliminate cracks in the welds.

Spot welds made in the 0.102-inch material with $\frac{1}{4}$ -inch-radius dome tips and with the maximum values of electrode force available in the welding machine were unsatisfactory from the standpoint of cracking. The weld diameters were small in proportion to the sheet thickness, and the penetration of fusion was high. The use of 6-inch-radius or possibly even larger, dome tips is also recommended for this gage when machines of sufficient electrode force and current capacity become available.

INTRODUCTION

Previous work on the spot welding of 0.020-, 0.040-, and 0.064-inch Alclad 24S-T (reference 1) showed that there were certain combinations of electrode force, electrode-type contour, current wave form and forge-force timing which permitted the production of sound welds over a wide range in current. That investigation also indicated that high-strength welds, free from defects, could be produced over a much wider range in welding current by using a variable-force cycle rather than a constant-electrode force. Limitations in the current and force capacity of the welding machine used for that investigation prevented welding the 0.064-inch material under the best conditions. With the present trend toward increasing size in aircraft structures, the use of heavier gages of the structural aluminum alloys will mount rapidly. The purpose of the present investigation, therefore, was to extend the earlier work to thicknesses of 0.064 inch and greater. Through the cooperation of the Taylor-Winfield Corporation a welding machine of considerably higher-current and electrode-force capacity was made available to the laboratory for this work.

This investigation was devoted to the selection of proper combinations of the welding variables to permit the production of high-strength welds suitable for primary aircraft structures over the widest possible range in welding current. The material used for the work was Alclad 24S-T in thicknesses of 0.064, 0.081, and 0.102 inch. As in previous studies, the effects of the variables upon weld quality were observed by plotting strength-current characteristics. In each case the average value of the strength of three standard shear specimens (reference 2) was plotted as a function of the welding current. For each set of conditions the current range between the values below which dud welds occurred and above which the welds expelled was covered where possible. Defects in the welds are indicated on these curves by means of appropriate symbols.

This investigation, conducted at the Rensselaer Polytechnic Institute, was sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics.

WELDING EQUIPMENT

The welding in this investigation was performed with a Taylor-Winfield Hi-Wave condenser-discharge welder, type HWRD-36-3CCIT. This machine was equipped with a dual-pressure system (reference 3) and was capable of delivering a maximum electrode force of 5000 pounds. The machine ordinarily delivered the forge and weld forces in a constant ratio of approximately 2.6:1, but slight modification through the use of an auxiliary air tank and an additional pressure regulator and gage permitted

changing this ratio almost at will. For convenience, a constant forge-to-weld force ratio is to be recommended in production machines. In this particular machine the manufacturer's choice of a ratio of 2.6:1 was found to be highly satisfactory.

The maximum peak-current output of the welder was 74 kiloamperes with a transformer-turns ratio of 450:1, a condenser capacitance of 2640 microfarads and a condenser voltage of 3000.

This machine was designed to provide a very rapid increase in electrode force from the value used for welding to that for forging, the time required for this increase being a matter of only 8 milliseconds. A very rapid build-up in forge force such as this is highly essential when welding thin-gage materials with a variable electrode-force cycle and a steep current wave form. For welding heavier gages when shallower current wave forms are used, a more gradual build-up in forge force would be satisfactory. It should be emphasized, however, that in no case should the forge force start to rise before the peak current has passed, and it should reach its maximum before the weld has cooled sufficiently to resist plastic deformation. If the forge force is applied too soon, or in other words if the time from the peak current to the application of the maximum forge force is too short, excessive sheet separation will result. Experience has shown that maximum benefits from welding with a variable electrode-force cycle are realized only when the forging is timed very accurately with respect to the peak welding current. When several gages of material are welded on the same machine, provision should also be made for varying the forge time delay over a wide range. These provisions of accuracy and latitude in the timing of the forge delay were adequately cared for in the design of the machine used for this investigation.

The throat depth of the machine was 36 inches, and for this work a horn spacing, from center to center, of $11\frac{1}{2}$ inches was used throughout. The latter dimension included a fine-wire resistance strain gage mounted on the lower electrode holder.

DEFINITIONS

The following are definitions of terms used in this report:

Weld force - force on the electrodes during the time in which fusion takes place

Forge force - total electrode force applied after the passage of the peak welding current for the purpose of eliminating cracks

Forge timing - time in milliseconds from the start of flow of welding current until the electrode force starts to rise for forging

Average rate of current rise - peak current divided by the time to peak

The sketch in figure 1 is presented to illustrate further the significance of these terms.

The time from peak current to maximum forge force, indicated in figure 1, is most significant in the proper application of forging. It measures the delay that must elapse from the completion of the weld, which is approximately at the peak of the welding current, until the weld has cooled sufficiently to avoid distortion, but not so much that the forging force is ineffective in preventing cracks.

ANALYSIS OF THE PROBLEM

Sound spot welds in aluminum alloys are obtained through proper selection of the electrode force for welding, electrode tip contour, current magnitude and wave form, and forge timing, if forging is necessary. The defects to be considered primarily are cracking, expulsion, excessive sheet separation, or the occurrence of dud welds due to insufficient current. The tendency toward the occurrence of cracking and expulsion decreases; whereas sheet separation increases with increasing electrode force for welding, if other welding variables are held constant. Sharper radius tips and steeper current wave forms increase the tendency toward expulsion. Too short a delay in time from the peak current to the application of forging results in excessive sheet separation, whereas too long a delay renders the forging ineffective in eliminating cracks.

There are two types of pressure cycle in common use for the spot welding of aluminum alloys. In one case the fusion takes place under a constant value of electrode force, and this force is maintained until the weld has completely cooled. In the other type of cycle the fusion also takes place at a constant electrode force, but after the weld has been made and while it is cooling the electrode force is increased for the purpose of compensating for the shrinkage which takes place; thus cracks are eliminated.

In spot-welding Alclad 24S-T, sound welds free from cracks, expulsion, and excessive sheet separation may be produced over a wider range in current with higher values of shear strength if a variable force cycle is used rather than a constant electrode force. This ability to produce sound welds is due to the fact that in the welding of this alloy, cracking tends to occur

at lower values of current than expulsion. In selecting the magnitude of a constant electrode force, the tendency for cracking in the welds must be balanced against the tendency for excessive sheet separation. With a variable force cycle, however, the tendency for expulsion may be balanced against the tendency for excessive sheet separation. Cracking may be disregarded in selecting the weld force, because it can be prevented by proper application of the forging force. The lesser tendency for expulsion to occur in the welding of Alclad 24S-T may be attributed to the gasket effect of the soft surface cladding.

In summarizing this discussion it should be emphasized that the optimum electrode force for the welding of clad alloys, when using a variable force cycle, is likely to be quite different from that used with a constant force cycle. The optimum weld force in a variable cycle is that which permits the production of welds over the greatest possible range in welding current with freedom from expulsion and excessive sheet separation, regardless of the occurrence of cracks. A forge force of sufficient magnitude, timed properly with respect to the peak current, is relied upon to eliminate cracks. Use of electrode forces during welding which are lower than the optimum will result in expulsion of metal from welds of smaller size. Electrode forces higher than the optimum will result in excessive sheet separation associated with welds of smaller size. The optimum weld force varies with the material thickness and tip contour.

In welding with a constant force cycle, the elimination of cracks usually requires a higher weld force than if forging were applied. This higher weld force results in excessive sheet separation which also limits the size of satisfactory welds that can be produced. The optimum weld force in a constant force cycle, therefore, is that force which permits the production of welds over the greatest possible range in welding current with freedom from cracks, expulsion, and excessive sheet separation. The optimum weld force will be higher and the maximum current range for sound welds narrower for a constant force cycle than for a variable force cycle, when spot-welding alloys in which the tendency for cracking is greater than the tendency for expulsion.

In spot welds in most of the structural aluminum alloys the tendency for cracking is more pronounced than the tendency for expulsion, although the difference in tendencies is somewhat greater in clad alloys than in bare alloys. This is probably due to the sealing effect of the cladding which was mentioned previously. In welding other alloys, such as 3S-1/2H, 52S-1/2H, and 61S-T, in which the cracking tendency is equal to or less than the expulsion tendency, there is no advantage in using a variable force cycle (reference 4). In welding these alloys the weld force must be set higher to offset the increased tendency toward expulsion. This may be done with less danger of excessive sheet separation than with the clad structural alloys. This higher weld force apparently is sufficient to prevent cracking below the expulsion limit.

From this analysis it should not be inferred that the use of optimum values of weld force is always required in spot-welding aluminum alloys. The purpose in determining optimum weld forces is to show what the best possible results are for any given conditions of material thickness and tip contour. In many instances, for nonstructural parts sound welds of lower shear strength or high-strength welds containing small amounts of defects are satisfactory. Welding equipment with insufficient electrode force and current capacity to permit welding a given material under optimum conditions will, in those cases, still be adequate.

DISCUSSION OF RESULTS

0.064-Inch Alclad 24S-T

In discussing the spot welding of 0.064-inch Alclad 24S-T it first may be well to consider the results obtained with thickness in reference 1 in which those results are presented graphically in figures 24 and 25. Data on the wave form and forge timing are shown in table IV of the same reference. The results indicated that neither a weld force of 800 pounds nor of 1600 pounds, in conjunction with a forge force of 2400 pounds (maximum for that machine), was satisfactory for 0.064-inch Alclad 24S-T, using either 2 $\frac{1}{2}$ - or 4-inch-radius dome tips. The use of a steep wave form was more desirable than a shallow wave form, within certain limitations. Dome tips of 4-inch radius were judged to be superior to the 2 $\frac{1}{2}$ -inch-radius domes for the 0.064-inch material. The larger radius tips permitted the production of larger welds without excessive sheet separation or expulsion.

The foregoing results showed that, to obtain welds of reasonable strength without objectionable sheet separation and expulsion, it was necessary to use 4-inch-radius electrodes. With these tips the available forge force was inadequate to avoid cracking. The importance of proper timing of the application of the forge force was also evident from the results mentioned.

With these facts in mind, welding conditions were selected which resulted in the characteristic curve (fig. 2). This showed a considerable improvement over the results of the earlier work. The machine settings and chemical-surface-treatment specifications are presented in table I. The maximum average shear strength for radiographically sound welds approached 1500 pounds. The range in peak current over which sound welds from 690 pounds (Army minimum strength) to 1500 pounds were produced was approximately 18,000 amperes. This was considered to be a very satisfactory working range. The approximate slope of the curve is 46 pounds per kiloampere, which indicates the desirable fact that the shear strength was only moderately sensitive to changes in the welding current.

Raising the weld force to a value greater than 1600 pounds in order to increase the maximum obtainable weld size before expulsion occurred was unsuccessful. With a weld force of 1800 pounds, excessive sheet separation (greater than 10 percent of the thickness of a single sheet) was introduced in the sound-weld points at the upper end of the curve. A weld force of 1600 pounds was, therefore, considered optimum for this thickness using a 4-inch-radius-dome-tip contour. The forge force of 3600 pounds was about the minimum that was adequate for these conditions of tip contour and weld force.

Although these results represented a considerable improvement over past performances, it may in the future be desirable to produce even stronger welds in this material. Indications are that this can be done through the use of 6-inch-radius dome tips. The electrode-force and current requirements would be expected to increase greatly under such conditions, however.

In figure 3 are presented photomicrographs of a typical spot weld in 0.064-inch Alclad 24S-T from a series of welds having an average shear strength of 1380 pounds. The picture at a magnification of 10X shows the weld to be sound and well-centered in the sheets, having a penetration of about 75 percent in each sheet. The photomicrograph at 100X shows the typical equal-axis grain structure at the center of the weld surrounded by the columnar grains. The heat-affected zone of incipient fusion and overaging is observed to be rather wide, but this is normal for this thickness of material. The protrusion of the cladding into the weld nugget is considered normal.

0.081-Inch Alclad 24S-T

With the knowledge gained from welding the 0.064-inch thickness, an attempt was made to select welding conditions for the 0.081-inch gage. The results of the conditions finally arrived at are presented in the strength-current characteristic of figure 4. The machine settings are shown in table II.

The maximum average shear strength for radiographically sound welds in this thickness of material, using these welding conditions was about 1700 pounds. Spot welds having an average shear strength of 1050 pounds (Army minimum value) to 1700 pounds were produced over a current range of approximately 13,000 amperes. Although satisfactory, this current range was not so wide as that obtained for the 0.064-inch material. The approximate slope of the curve is 48 pounds per kilomapere which compares very favorably with the value of 46 pounds per kiloampere for the 0.064-inch material. Attempts to increase the sound-weld range were unsuccessful because of the introduction of excessive sheet separation.

The only feasible method of increasing the weld size was to use larger-radius dome tips. The results obtained through the use of 6-inch-radius domes are presented in the curve of figure 5. The welding conditions are presented in table III. These results indicated that much stronger welds could be obtained with freedom from expulsion than was possible with the 4-inch-radius tips. The limitation in current capacity of the machine required a decrease in the weld force in order to make these larger welds. This is the reason for the decrease from the 2000-pound weld force for the 4-inch-radius tips to the value of 1800 pounds used in this case. Actually the weld force should have been increased for the larger radius tips, and this would have been done if sufficient current capacity had been available. Because the weld and forge forces were varied in a constant ratio, a decrease in the weld force necessitated a decrease in the forge force. The forge force used, therefore, was 300 pounds less than the capacity of the machine and was sufficient to eliminate cracks only over a very narrow range in welding current. A much higher forge force than the 5000-pound maximum provided by this machine would have been necessary to eliminate cracks in the larger welds.

With a forge force of sufficient magnitude to eliminate the cracks, sound welds having shear strengths up to at least 2100 pounds could be produced, other conditions remaining the same. In view of the fact that a weld force of 2000 pounds was considered optimum for this gage when using 4-inch-radius domes, it is to be expected that the value of 1800 pounds is far below the optimum for 6-inch-radius dome tips. The use of a weld force approaching the optimum value, together with a forge force of sufficient magnitude to eliminate cracks, would be expected to raise the maximum strength for sound welds in this gage appreciably above 2100 pounds.

Photomicrographs of a typical spot weld in 0.081-inch material are presented in figure 6. This particular weld was made with 4-inch-radius dome tips under the same conditions as the welds having an average shear strength of 1440 pounds, as shown in figure 4. The picture taken at a magnification of 10X shows the weld to have slightly more penetration in one sheet than in the other. The weld is uniform in shape, however, and of sound structure. The picture at 100X shows the typical equal-axis and columnar dendritic zones of the weld, again surrounded by a wide zone of incipient grain-boundary fusion and overaging, as was observed in the 0.064-inch thickness. The protrusion of the cladding into the weld nugget is normal.

0.102-Inch Alclad 24S-T

Inasmuch as it had been demonstrated that the welding machine possessed insufficient capacity to weld the 0.081-inch thickness under optimum conditions using 6-inch-radius dome tips, it was considered

impracticable to attempt any welding with these tips on the 0.102-inch material. The highest values of electrode force available in the welding machine were chosen, and 4-inch-radius dome tips were employed. The welding conditions are shown in table IV. The resulting strength-current characteristic is presented in figure 7. Sound welds having strengths of from 1400 pounds to about 2000 pounds were produced over a current range of about 6000 amperes. The slope of the curve was approximately 100 pounds per kiloampere, much steeper than the curves for the 0.064- and 0.081-inch materials. These welding conditions are, of course, satisfactory only for joints in which high-strength, sound welds are not important. As in the case of the 0.081-inch material, the production of high-quality welds in the 0.102-inch thickness will have to wait for welding equipment of suitable capacity.

The metallographic structure of a typical spot weld in the 0.102-inch thickness of Alclad 24S-T is shown in figure 8. This weld was made under the same conditions as the 2560-pound welds of figure 7. The photomicrograph at 10X reveals that the diameter of this weld is relatively small in proportion to the thickness of the sheets. The cladding protrudes into the nugget a considerable distance, and the center of the weld shows evidence of a considerable amount of porosity and cracking. The end-weld structure of the spot weld is shown in the photomicrograph at 100X.

CONCLUSIONS

As a result of this investigation it may be concluded in general that welding machines equipped with dual-pressure systems are even more important for the production of spot welds of high quality in the heavier gages of Alclad 24S-T than has been reported in previous investigations with lighter gages of this alloy. The results of this investigation were subject to the following machine limitations: a forge force of 5000 pounds and a peak current of 74 kilocamperes, obtained with a condenser capacitance of 2640 microfarads, a condenser voltage of 3000, and a transformer-turns ratio of 450:1. A welding machine with much higher electrode force and current capacity is required in order to obtain maximum benefits in spot-welding Alclad 24S-T in thicknesses of 0.081 inch or greater.

Electrodes of 4-inch radius are suitable for all gages of Alclad 24S-T from 0.020 to 0.064 inch. When forging is to be applied, the optimum electrode force during welding, in pounds, should be about 25 times the single-sheet thickness, in mils, using this tip contour. For gages heavier than 0.064 inch, it is desirable to use larger-radius electrodes. With these tips, somewhat higher electrode forces during welding are preferable.

In welding Alclad 24S-T up to 0.081 inch in thickness, it has been observed that, when the optimum value of weld force is employed for a particular thickness of material and tip contour, a forge force of 2.5 times the weld force is adequate to eliminate cracks in the welds up to the point on the strength-current characteristic at which expulsion starts. This ratio of forge-to-weld force will probably also be found adequate for the heavier gages when sufficient machine capacity permits their welding under optimum conditions. The specific conclusions of this work are summarized as follows:

1. Sound spot welds of high strength in 0.064-inch Alclad 24S-T were produced over an extremely wide range in welding current when optimum welding conditions were used with 4-inch-radius dome tips. These conditions were:

Weld force, pounds	1600
Forge force, pounds	3600
Forge timing, milliseconds	65
Time to peak current, milliseconds	16
Time from peak current to maximum forge force, milliseconds	57
Average rate of current rise (center of strength-current characteristic), amperes per millisecond	3500

If higher-strength spot welds were desired in this material, they could be procured by using 6-inch-radius dome tips, provided the requirements of higher electrode force and welding current were met.

2. Sound spot welds in 0.081-inch Alclad 24S-T were produced over a reasonably wide range in welding current when optimum welding conditions were used with 4-inch-radius dome tips. These conditions were:

Weld force, pounds	2000
Forge force, pounds (maximum)	5000
Forge timing, milliseconds	110
Time to peak current, milliseconds	27
Time from peak current to maximum forge force, milliseconds	91
Average rate of current rise (center of strength-current characteristic), amperes per millisecond	2100

Spot welds of much higher shear strength were obtained in this thickness of material when 6-inch-radius dome tips were used. The limitation in current capacity of the machine, however, required the use of a lower weld force in order to obtain these larger welds. Actually, the weld force should have been increased for the larger-radius tips. Because the weld and forge forces were varied in a constant ratio, a decrease in weld force necessitated a decrease in forge force. The forge force used, therefore, was 300 pounds less than the capacity of the machine

and was sufficient to eliminate cracks only over a very narrow range in welding current. A much higher force than the 5000-pound maximum available would have been necessary to eliminate cracks in the larger welds.

3. Sound spot welds in 0.102-inch Alclad 24S-T were produced over a very narrow range in welding current with 4-inch-radius domes and with the maximum electrode force available in this machine. As was the case with 0.081-inch material, much more satisfactory welds could have been obtained through the use of 6-inch-radius dome tips and a welding machine of sufficient capacity.

Welding Laboratory
Rensselaer Polytechnic Institute
Troy, N. Y., April 9, 1945

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TABLE I.-- WELDING CONDITIONS FOR 0.064-INCH ALCLAD 24S-T

CONDENSER-DISCHARGE MACHINE

[These conditions were optimum for this thickness and tip contour.]

Electrode tips	4-inch-radius domes
Electrode force	1600 pounds (weld) 3600 pounds (forge)
Transformer-turns ratio	300:1
Condenser capacitance	1440 microfarads
Condenser voltage	2000 to 2700 volts
Forge timing	65 milliseconds
Surface treatment	Degreased in trichloroethylene. Treated 10 minutes in hydro- fluosilicic acid, H_2SiF_6 , 3 percent by volume, 75° F; rinsed in cold water, air-dried.

TABLE II.-- WELDING CONDITIONS FOR 0.081-INCH ALCLAD 24S-T

CONDENSER-DISCHARGE WELDER

[These conditions were optimum for this thickness and tip contour.]

Electrode tips	4-inch-radius domes
Electrode force	2000 pounds (weld) 5000 pounds (forge) (maximum)
Transformer-turns ratio	450:1
Condenser capacitance	2040 microfarads
Condenser voltage	2200 to 2700 volts
Forge timing	110 milliseconds
Surface treatment	Degreased in trichloroethylene. Treated 12 minutes in hydro- fluosilicic acid, H_2SiF_6 , 3 percent by volume, 75° F; rinsed in cold water; air-dried.

TABLE III.- WELDING CONDITIONS FOR 0.081-INCH ALCLAD 24S-T

CONDENSER-DISCHARGE WELDER

[These conditions were not satisfactory for this thickness and tip contour. A weld force of 1800 pounds demanded current requirements up to the maximum capacity of the machine. This weld force is probably at least 600 pounds below the optimum value for this thickness and tip contour.]

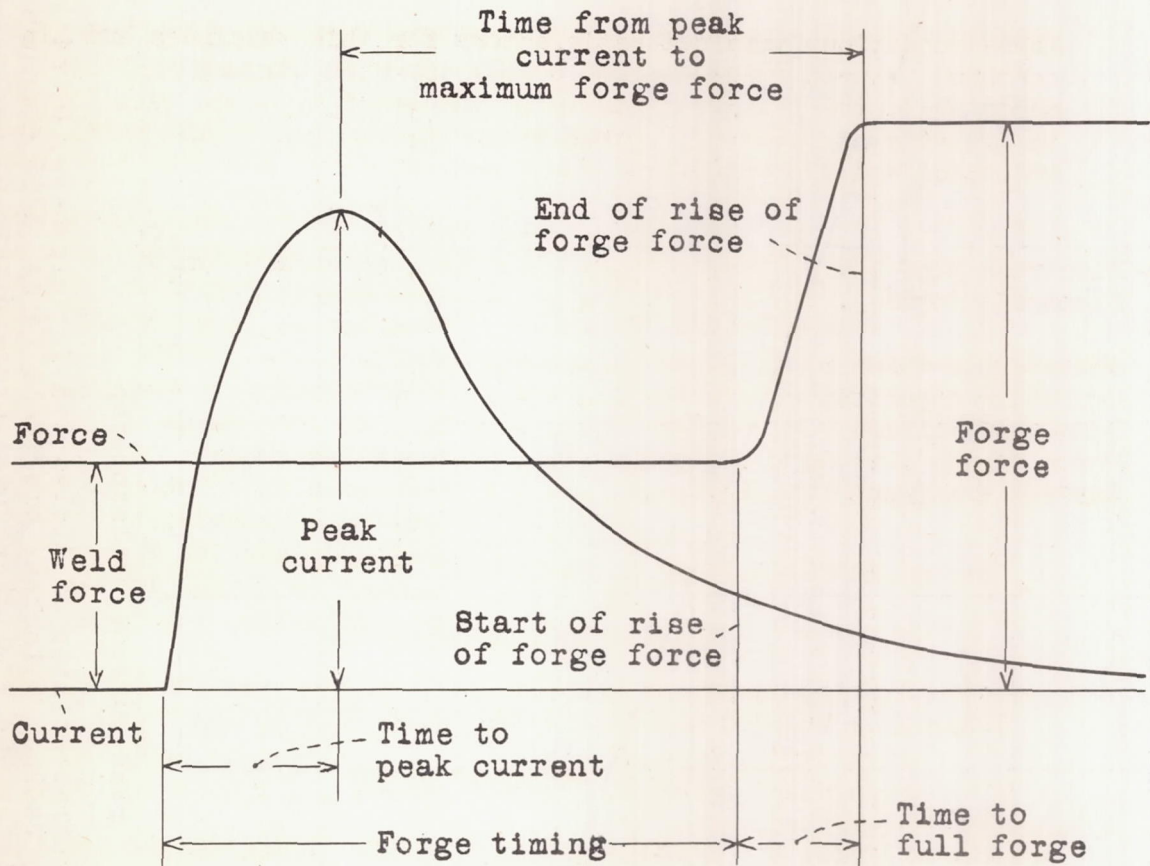
Electrode tips	6-inch-radius domes
Electrode force	1800 pounds (weld) 4700 pounds (forge)
Transformer-turns ratio	450:1
Condenser capacitance	2640 microfarads (maximum)
Condenser voltage	2100 to 2900 volts
Forge timing	93 milliseconds
Surface treatment	Degreased in trichloroethylene. Treated 10 minutes in hydro- fluosilicic acid, H_2SiF_6 , 3 percent by volume, 75° F, rinsed in cold water, air-dried.

TABLE IV.- WELDING CONDITIONS FOR 0.102-INCH ALCLAD 24S-T

CONDENSER-DISCHARGE WELDER

[These conditions are unsatisfactory for this thickness and tip contour, provided high-strength, sound welds are desired. The use of 6-inch-radius tips is recommended when machines of sufficient capacity are available.]

Electrode tips	4-inch-radius domes
Electrode force	2000 pounds (weld) 5000 pounds (forge) (maximum)
Transformer-turns ratio	450:1
Condenser capacitance	2640 microfarads (maximum)
Condenser voltage	2300 to 2900 volts
Forge timing	117 milliseconds
Surface treatment	Degreased in trichloroethylene. Treated 15 minutes in hydro- fluosilicic acid, H_2SiF_6 , 3 percent by volume, 75° F, rinsed in cold water, air-dried.



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Figure 1.- Current and force relations in dual-pressure cycle for condenser-discharge welding machine.

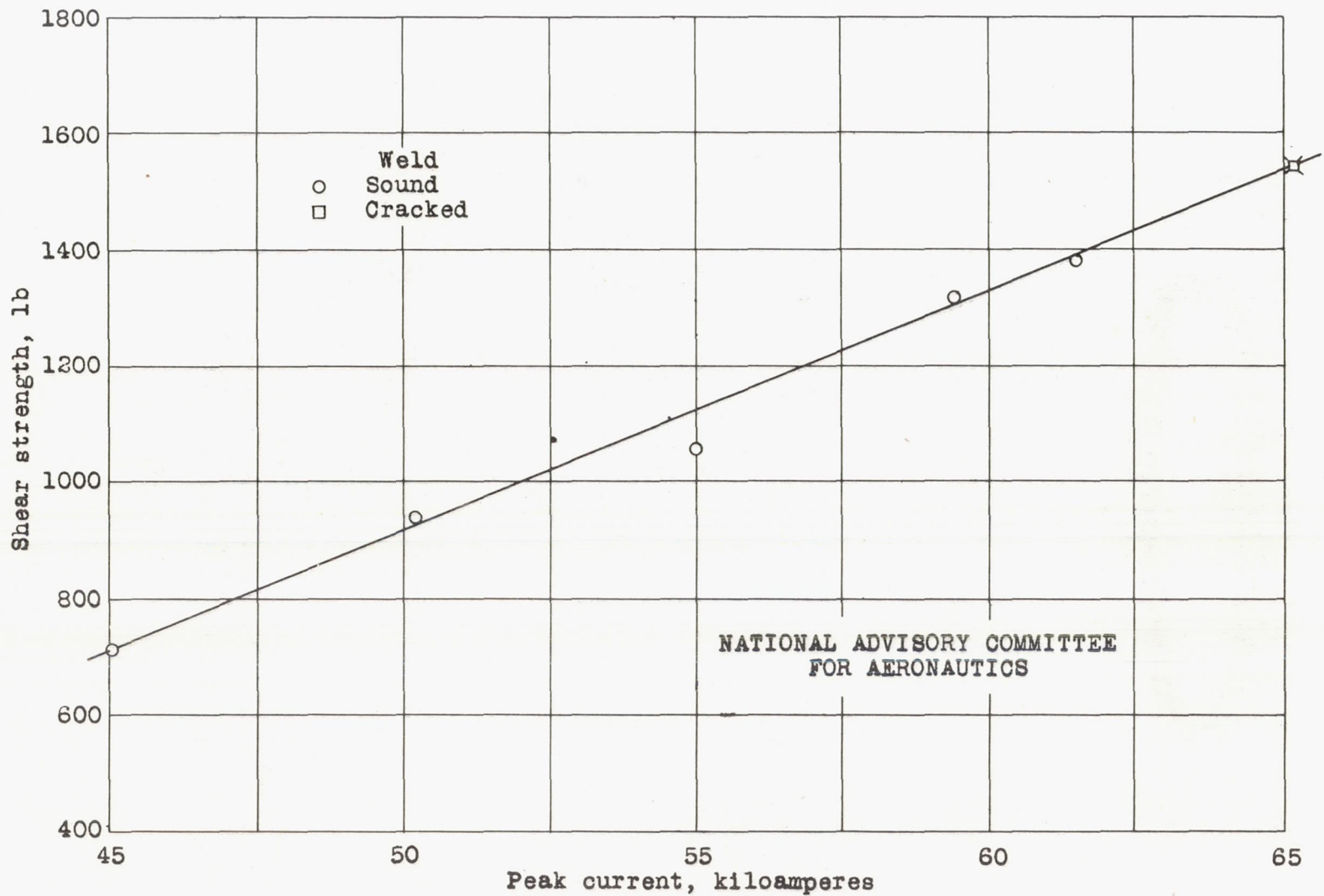
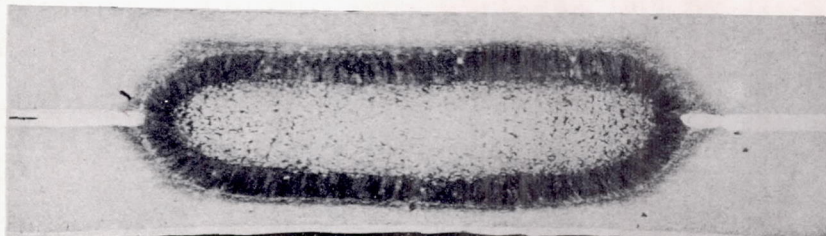
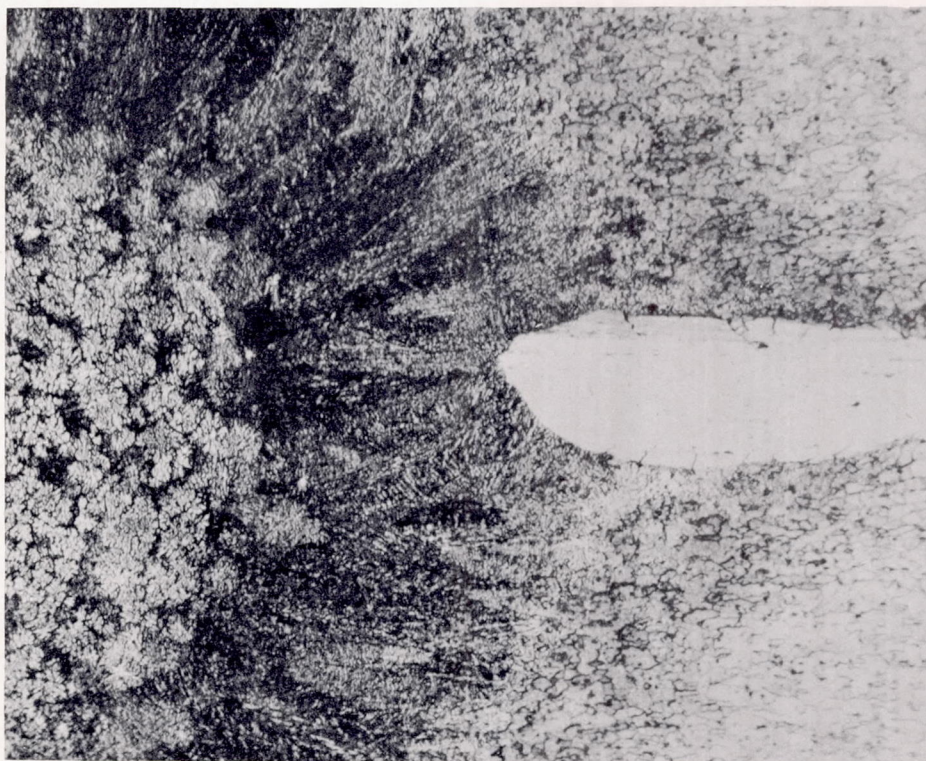


Figure 2.- Strength-current characteristic of Alclad 248-T. Thickness, 0.064 inch; electrode dome-tip radius, 4 inches; electrode force, 1600 pounds (weld), 3600 pounds (forge); forge timing, 64.7 milliseconds; average rate of current rise, 3485 amperes per millisecond.



10X

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100X

Figure 3.- Photomicrographs of spot weld in 0.064-inch
Alclad 24S-T.

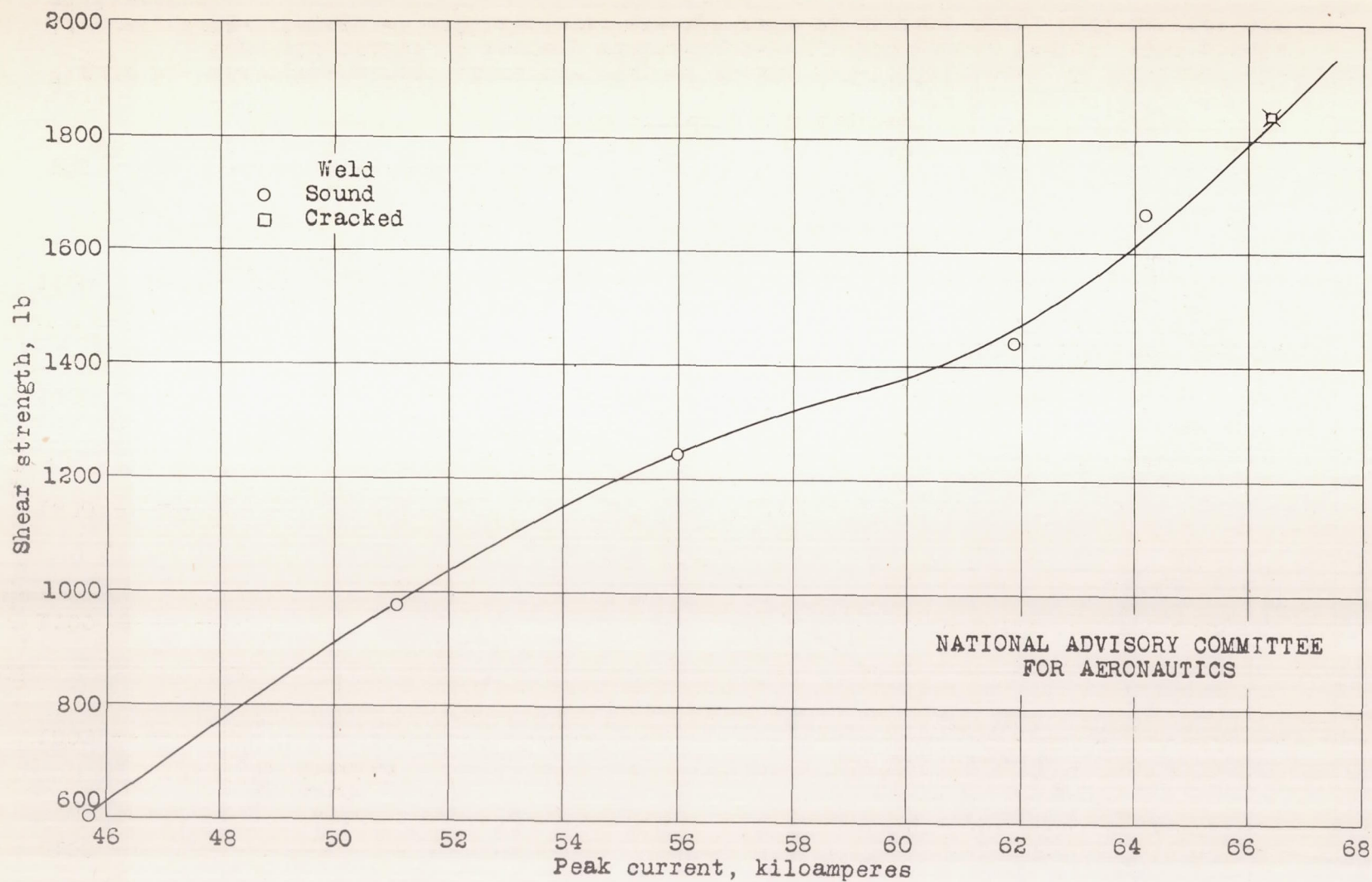


Figure 4.- Strength-current characteristic of Alclad 24S-T. Thickness, 0.081 inch; electrode dome-tip radius, 4 inches; electrode force, 2000 pounds (weld), 5000 pounds (forge); forge timing, 110 milliseconds; average rate of current rise, 2100 amperes per millisecond.

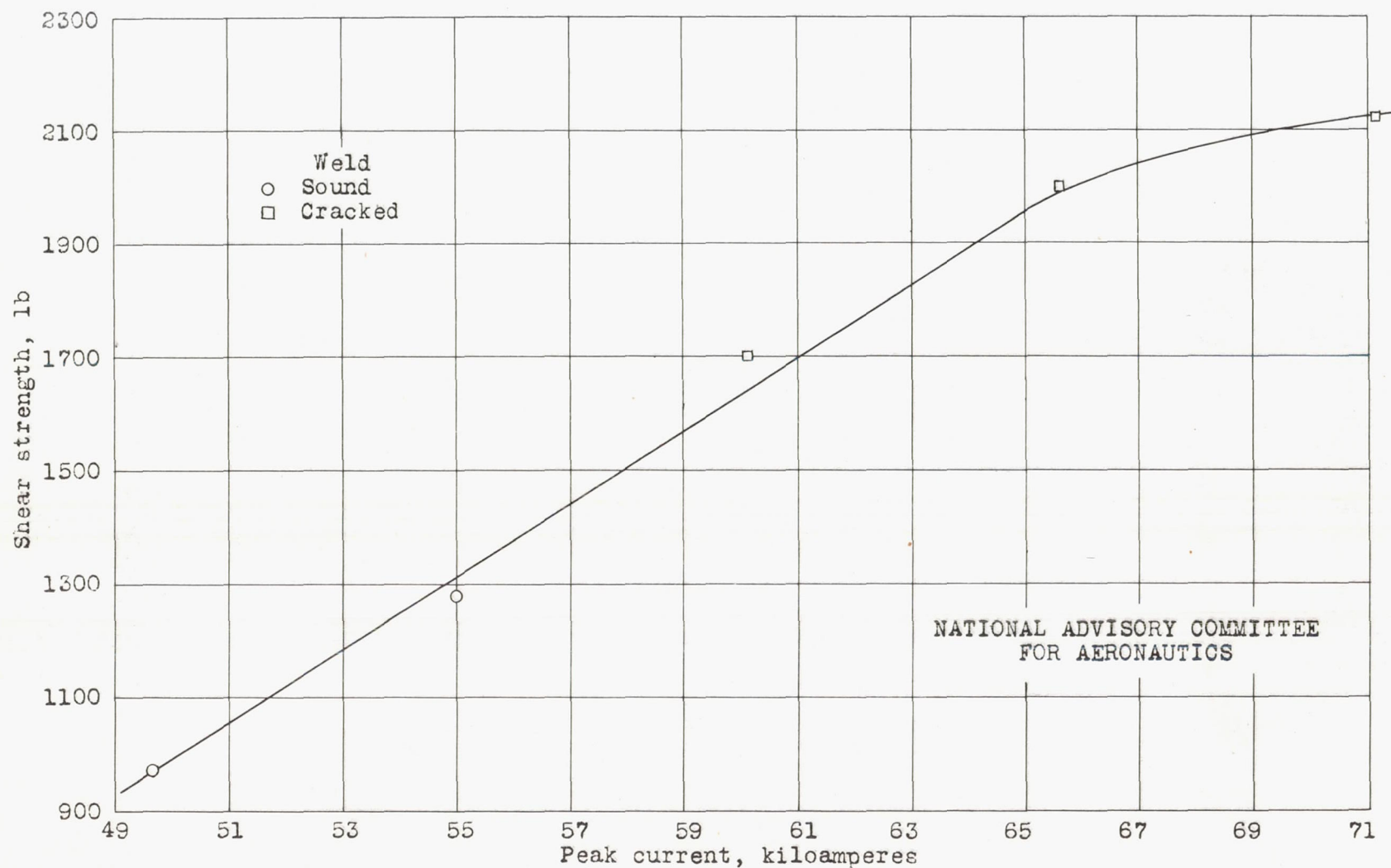
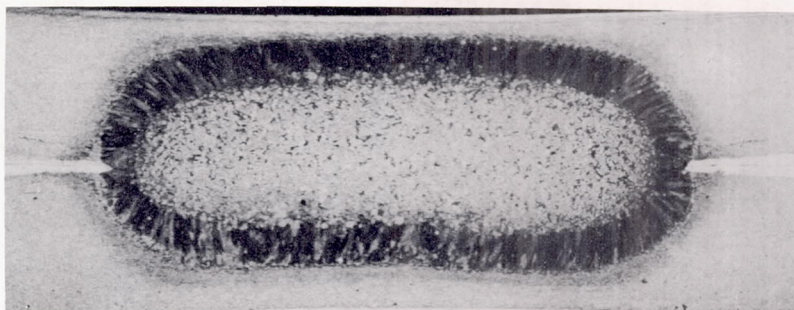


Figure 5.- Strength-current characteristic of Alclad 24S-T. Thickness, 0.081 inch; electrode dome-tip radius, 6 inches; electrode force, 1800 pounds (weld), 4700 pounds (forge); forge timing, 93 milliseconds; average rate of current rise, 1925 amperes per millisecond.



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Figure 6.- Photomicrographs of spot weld in 0.081-inch
Alclad 24S-T.

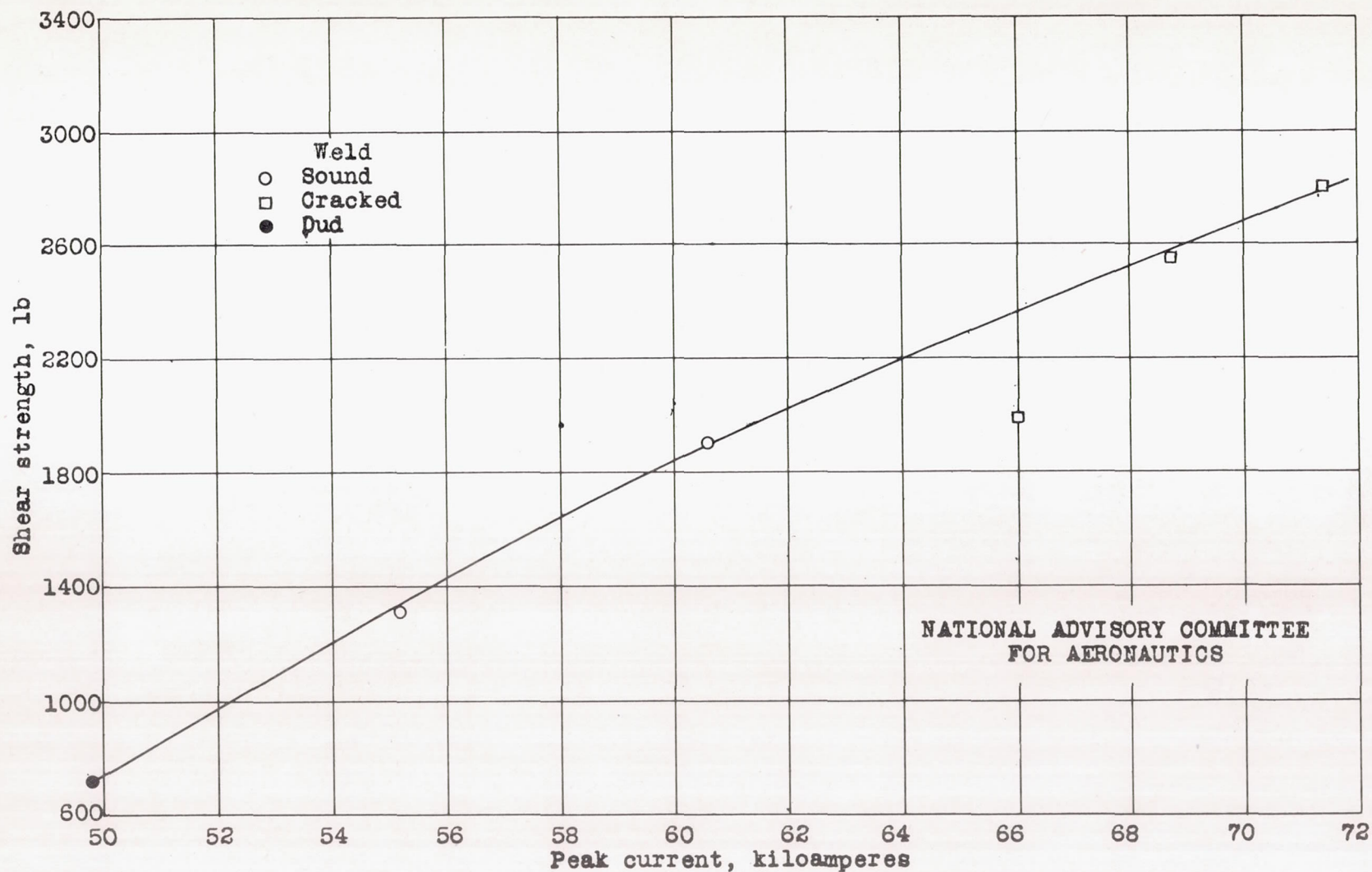
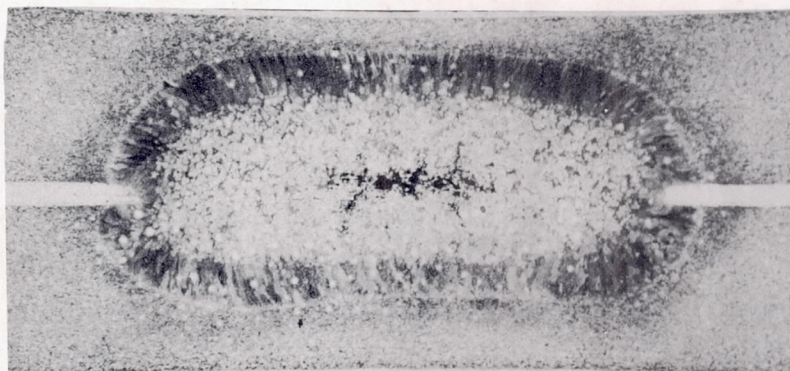
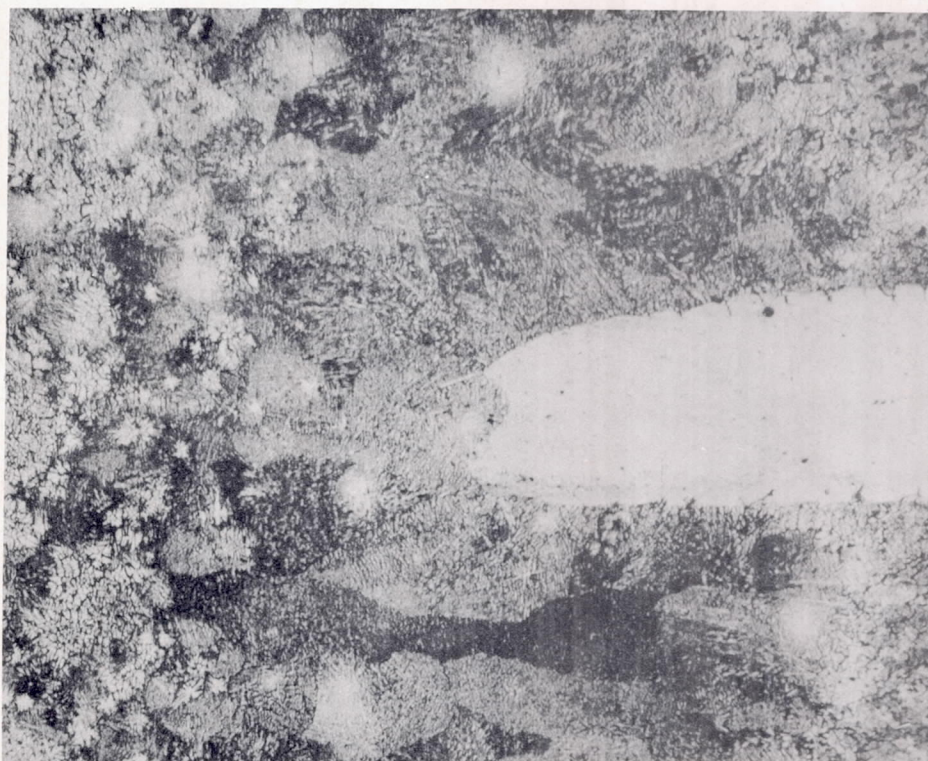


Figure 7.- Strength-current characteristic of Alclad 24S-T. Thickness, 0.102 inch; electrode dome-tip radius, 4 inches; electrode force, 2000 pounds (weld), 5000 pounds (forge); forge timing, 117 milliseconds; average rate of current rise, 1800 amperes per millisecond.



10X

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Figure 8.- Photomicrographs of spot weld in 0.102-inch
Alclad 24S-T.